Fermi National Accelerator Laboratory

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SSC Dipole Coil Production Tooling*

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ABSTRACT

Superconducting Super Collider dipole coils must be produced to high precision to ensure uniform prestress and even conductor distribution within the collared coil assembly. Tooling is being prepared at Fermilab for the production of high precision 1M and 16.6M SSC dipole coils suitable for mass production. The design and construction methods builds on the Tevatron tooling and production experience. Details of the design and construction methods and measured coil uniformity of 1M coils will be presented.

INTRODUCTION

The Superconducting Super Collider will require approximately 8,000 dipole magnets 16.6M in length. Each magnet will have two inner and two outer coil assemblies. Each coil assembly must be made to exacting tolerances. Of primary concern is the cross sectional uniformity of individual conductor placement within the magnet assembly along its full length. In application, the coils are paired and assembled using laminated stainless steel clamping collars. The collars serve to compress or prestress the coils so as to resist the magnetic forces which act on the coil when energized. Redistribution of conductor placement within the coil from its specified design results in undesirable multipole fields. Variations in prestress which contribute to conductor placement errors have other undesirable effects. Areas of low prestress can allow conductor motion resulting in coil heating and subsequent quenching of the magnet below its design load. Areas of overly high prestress hasten the breakdown of the insulation system which can result in turn to turn coil shorting and magnet failure (Figure 1).

The coils are composite structures and as such each constituent is a possible contributor to coil conductor placement and size variations. The term size is always tied to a specific load. The prestress for the SSC will range from approximately 8 KPSI to 12 KPSI*. The constituents are the superconducting cable, the superconducting strands within the cable, the insulation; kapton and B-stage epoxy impregnated fiberglass tape (Figure 2), the epoxy in the fiberglass tape and the copper wedges as well as the application of the insulation onto the cable and wedges. All of these items require stringent quality control. In any event there is little the coil fabricator can do about them except follow criteria for accepting or rejecting their use in fabricating the coil. The burden on the coil fabricator is to assemble these components in a way which produces coils as good as the constiuents allow without adding variations. This burden is manifested in the tooling and procedures used in making the coils.

The coil production sequence for making coils is straight forward. The steps are not complex. What is important is the design and quality of the tooling and rigid conformance to procedures. Figure 3 illustrates the process.

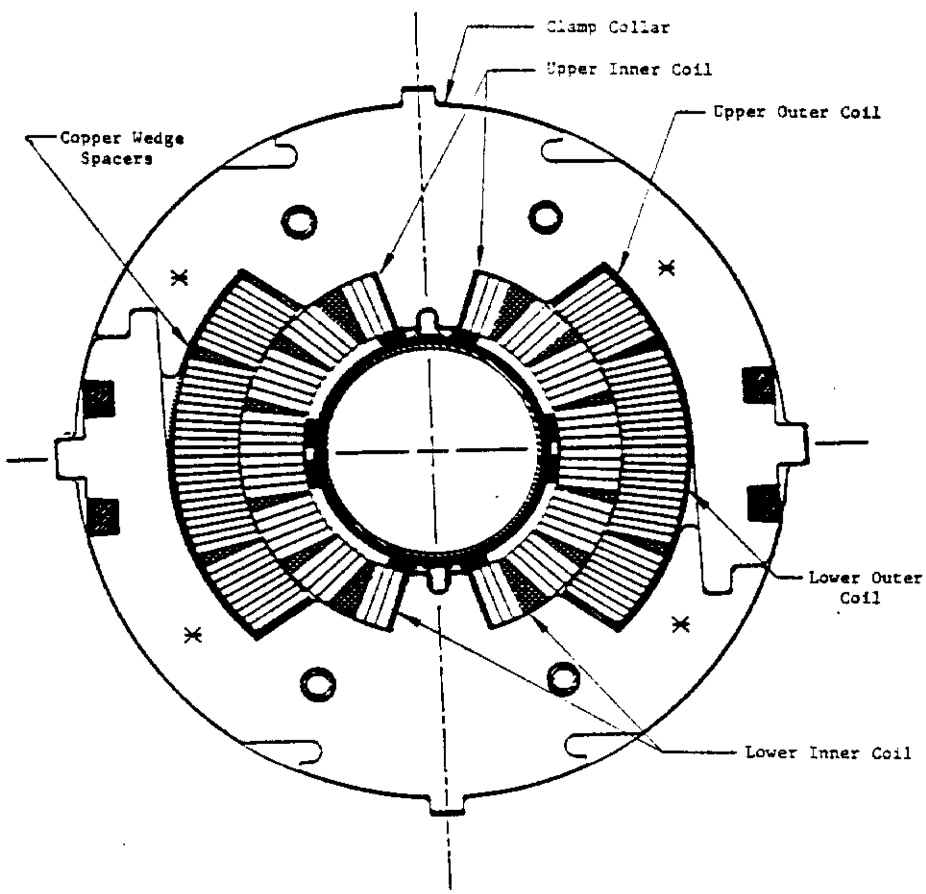


Figure 1. SSC Dipole - Collared Coil Cross Section

*The prestress range will be established from SSC Research and Development program.

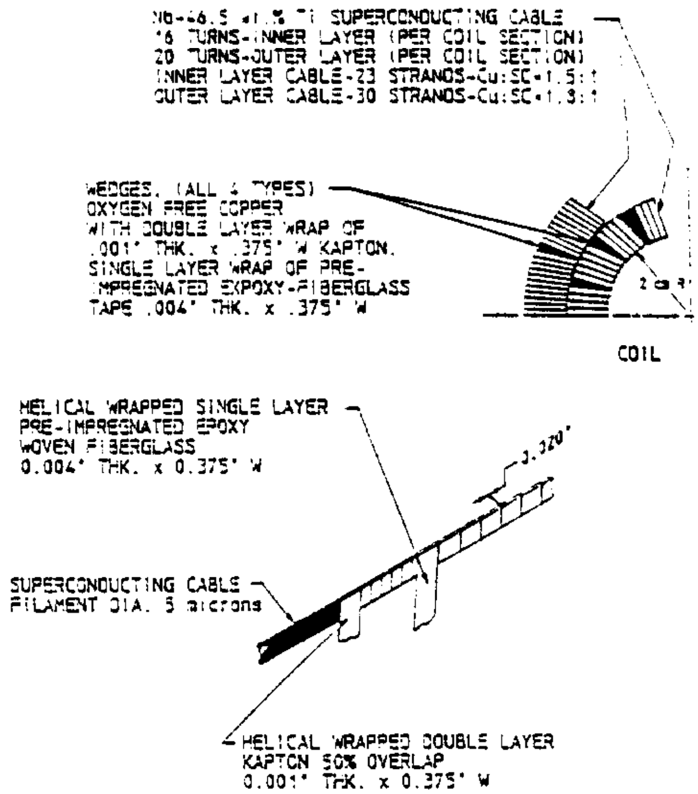


Figure 2. Coil Components

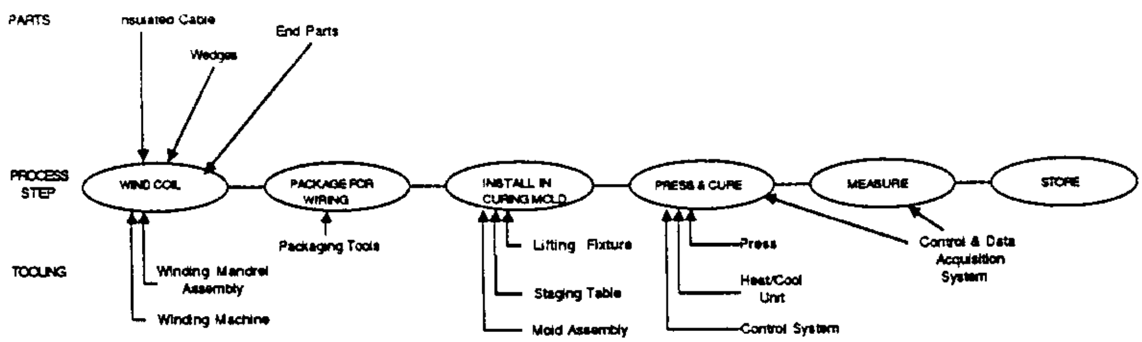


Figure 3. Coil Production Process Sequence

LAMINATED TOOLING

The Technical Support Group at Fermilab has designed and is in the process of assembling 16.6M tooling for winding and curing SSC C358D cross section coils. One meter tooling of like design has been completed and is starting to be used to produce a series of 1M coil for purposes of coil-end development[1] and the evaluation of the tooling itself. The tooling under construction is an outgrowth of our experience in the production of more than 1,000 magnets which are now in operation at Fermilab's accelerator, the Tevatron.

The tooling used in forming the coil structure is a closed cavity mold with the coil winding mandrel assembly being the male portion and the forming mold being the female portion. The insulated cable along with wedges and end components are wound onto the mandrel at constant tension, secured, and fitted to the mold cavity. The cavity formed is a long semi-cylinder of dimensions equivalent to the "as collared" coil size. During the development of the Tevatron tooling, we found it was very difficult to produce long tooling which satisfied the uniform cross section criteria. Our most frustrating problem was trying to achieve the required dimensional accuracy of the complex tooling shapes, a combination of radii and angles. Short tooling, (1 foot) could be produced, however long tooling with the same dimensional requirements exceeded convention machining capabilities. Compounding the problem was the requirement for many sets of identical tooling necessary to achieve the required coil production throughput. Besides the cross section problems, the tooling had to be massive so as not to distort the mold cavity during the high pressure molding process. This resulted in mold forms with high longitudinal stiffness. The stiffness imposed stringent flatness and straightness tolerances on both the tooling and the presses which closed the mold. Our solution was to use stacks of steel laminations for the tooling. The laminations could be stamped to high precision with piece parts of nearly identical size. With laminations we could create multiple tooling which was identical. Since the tooling was now a stack of laminations, longitudinal stiffness became nil, therefore, the tooling could easily comply to press platten irregularities.

The SSC tooling Fermilab is producing uses the lamination theme. Conventional machining methods are limited to precision items which have simple, easily machined geometries such as rectangular bars. Tooling components which involve radii and angles that are not practical for laminating are made using computer controlled electrical discharge wire cutting machining (EDM)[2] methods.

Figure 4 illustrates the outer coil winding mandrel assembly. The winding key is an EDM part. The curved portion of the mandrel is made of stacked laminations. A conventionally machined strongback carries the laminations. Figure 5 illustrates the same mandrel with the coil wound on it, packaged and ready to install in the form mold. The sizing bars are used to define the azimuthal cavity and are ground-bar stock. The sheet metal retainer serves to retain the coil to the mandrel and provide a smooth surface for the outer radius of the coil. Figure 6 illustrates the mold assembly. The body of the mold is stacked laminations tied together with full length tie rods. Full length tubes are installed in six places to provide for heating and cooling the mold. The tubes, low-carbon steel, are nominally .010" smaller in diameter than the lamination hole. Once installed, the tubes are expanded using ball swagging. Ball swagging is a process where a hard steel ball is forced through the tube using hydraulic pressure. As the ball progresses, the tube yields. The ball is sized to give intimate contact of the tube and the lamination providing a good thermo connection. The tubes are terminated at manifolds on each end for connection to a fluid heating/cooling system. Spring loaded roller assemblies are bolted to the "T" ways on the sides of the laminations and allow transport of the mold into the press following a guide rail. The ground steel bars fastened to the mold top are provided as an adjustable interface with the upper press platten. These bars can be shimmed to fine tune the azimuthal cavity size if required. The laminations are 1050 spheroidize annealed steel throughout. We would have preferred laminations produced by the fine-blanking[3] process for reasons of accuracy and edge finish but because of schedule demands opted for compound die stamped laminations with shaved edges at critical areas. All other steel components are 4150 HT alloy steel.

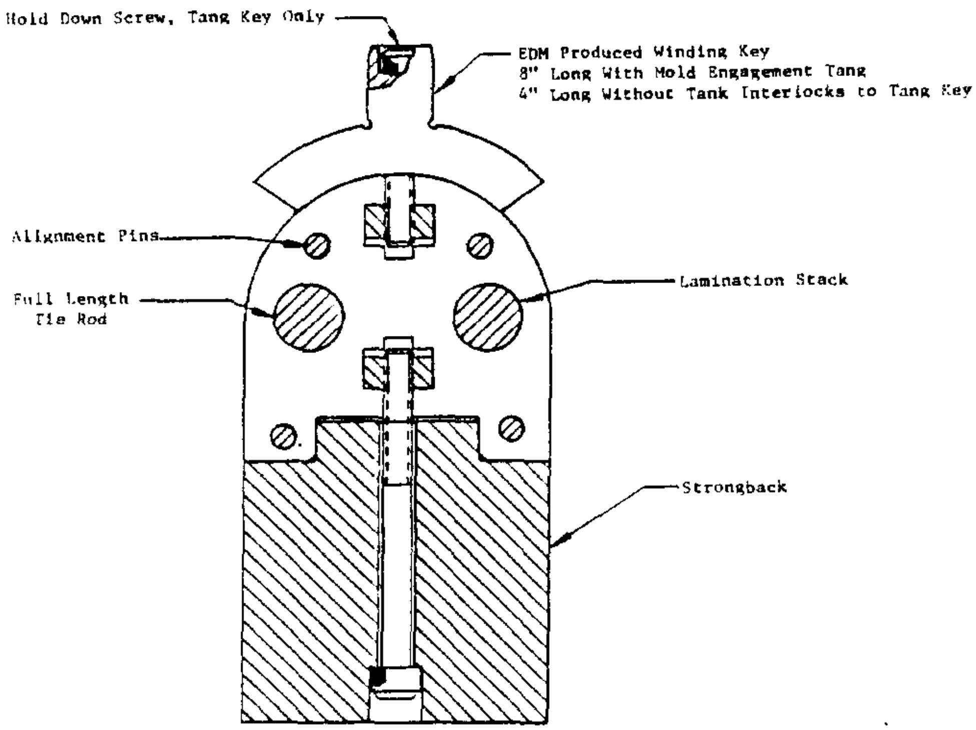


Figure 4. Outer Winding Mandrel and Winding Key Assembly - Length = 56'

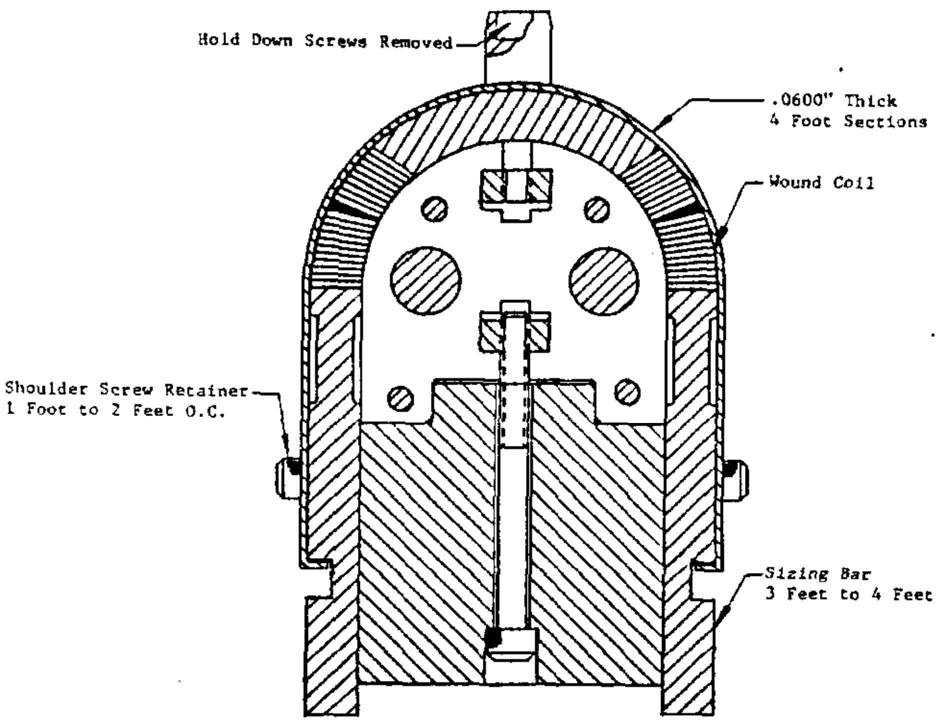


Figure 5. Packaged Outer Coil Ready to Install in Mold

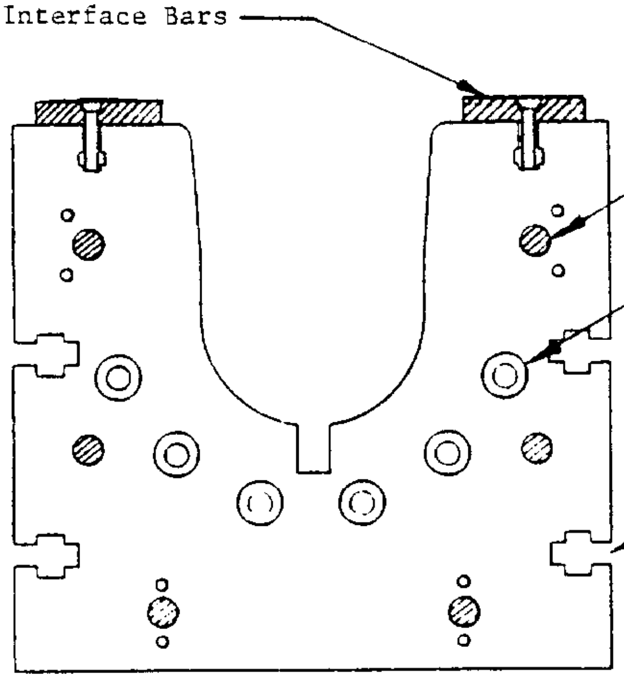


Figure 6. Laminated Outer Coil Mold Assembly - Length = 56'

Assembly of the laminated tooling has its own unique problems. Regardless of the accuracy of the lamination there is bound to be asymmetries in the lamination features. These asymmetries preclude flipping the lamination because the overlap of asymmetric features would effectively change the critical mold feature dimensions. To guard against accidental flipping, witness notches are provided in the stamping die. Because the laminations are not perfectly parallel, stacking can result in fanning of the stack. To avoid this, the coil material is measured before stamping and equal quantities of laminations are stamped with opposite sheet taper. Laminations of opposite but equal taper are then stacked alternately to avoid fanning. Before stacking can start the laminations must be deburred and cleaned. The stacking is done in stages. First a stack of approximately 6' length is made. Stacking pressure is approximately 300 psi. During this initial stack up, corrections are made to keep end to end parallelism to within .015" over 10". This is accomplished by the removal and replacements of a few laminations with appropriate taper. If the stack calls for a series of notched laminations at some interval (molds), it is accomplished at this point. Once the stack is deemed acceptable it is unstacked and reassembled in the same order with alignment pins installed. The alignment pins, 2" long roll pins, assure lamination to lamination alignment without the need for elaborate and extremely precise stacking surfaces. The completed 6' assemblies are then joined, using the roll pins, to form an uninterrupted stack of laminations. End plates are added and tie rods inserted to retain the stack. The coils have no straightness requirement, therefore, the tooling need be only straight enough to affect engagement. It should be noted that nothing in the tooling assembly process is allowed which would compromise the integrity of the laminated tooling's main attributes, i.e. uniformity and compliance. For this reason welding and or secondary machining of the assembly is not allowed. The design tolerance for the components allows a closed cavity mold accuracy of: radial uniformity of $\geq$ .0015" and azimuthal uniformity of $\geq$ .002" along the full length.

The process steps for utilization of the tooling is depicted in Figure 7. The tooling is designed to work in a two-stage press; i.e. the press must provide independent loading against the mandrel and the sizing bars. The intent here is to define the radial cavity before loading the coil azimuthally. The purpose is to achieve better conductor placement by not allowing the cable to cable radial interface to lockup through friction before radial placement is achieved. Figure 8 shows the applications of the loads during molding process.

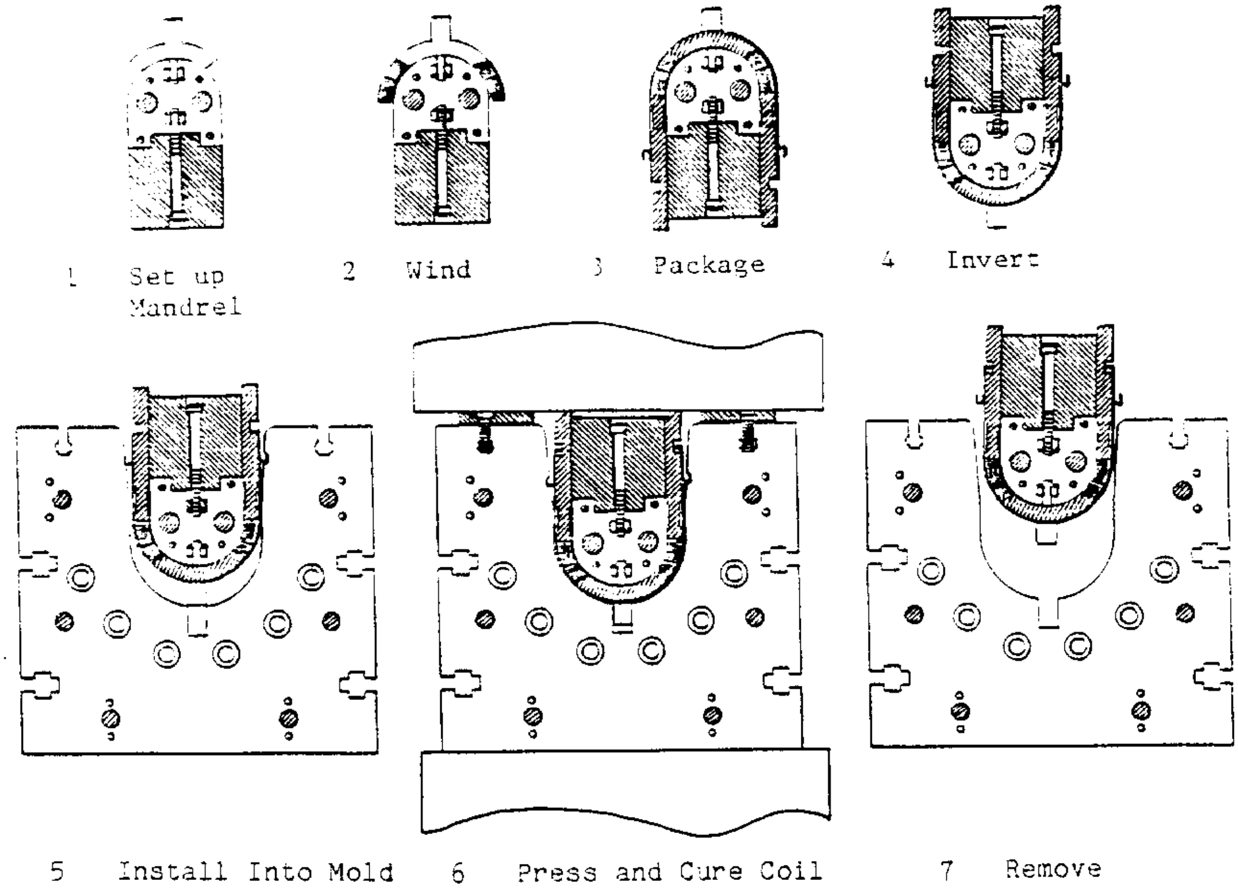


Figure 7. Coil Fabrication Process

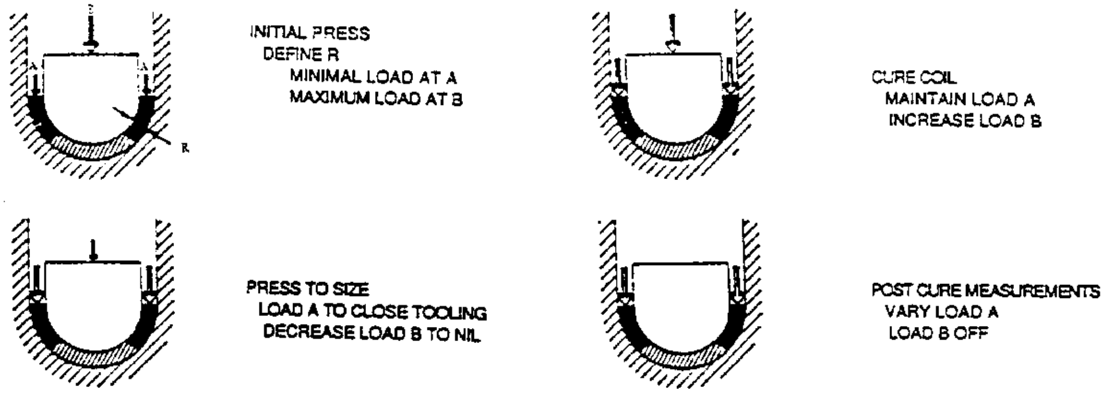


Figure 8. Coil Molding Cycle

CURING PRESS

The curing press under construction is shown in Figure 9. The press capacity is 3,333 lbs/in against the mandrel and 18,889 lbs/in against both sizing bars. The geometric design constraints on the press require that the plattens' longitudinal flatness be ≤ .001" between hydraulic cylinders and ≤ .001" at any transverse section under full load. The press will be fitted with load cells and LVDT's at 18" increments on both sides of the coil to enable measurement of stress and strain of the coil in the press during and after the mold cycle. Outputs will be recorded by a computer operated data acquisition system. The hydraulic and heating/cooling system will be controlled by the same computer.

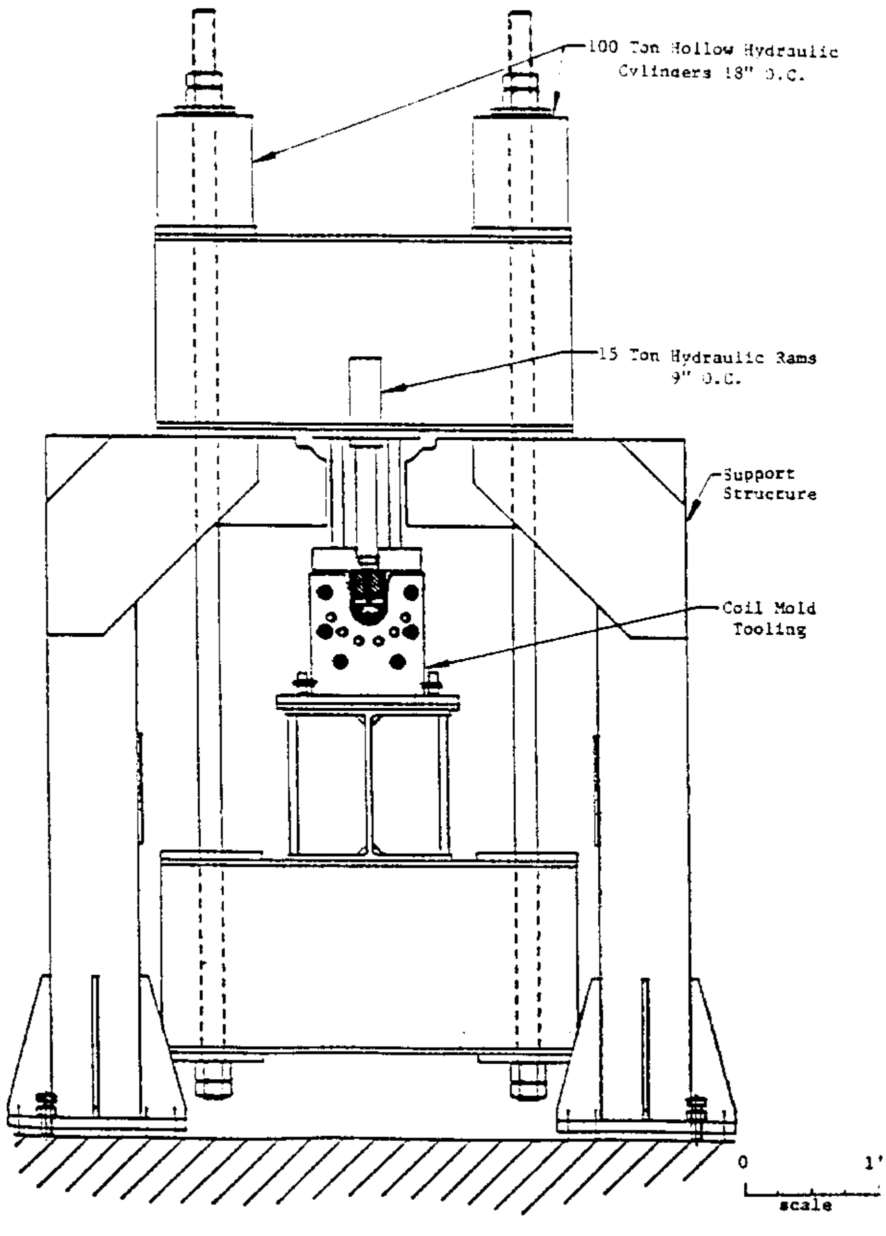
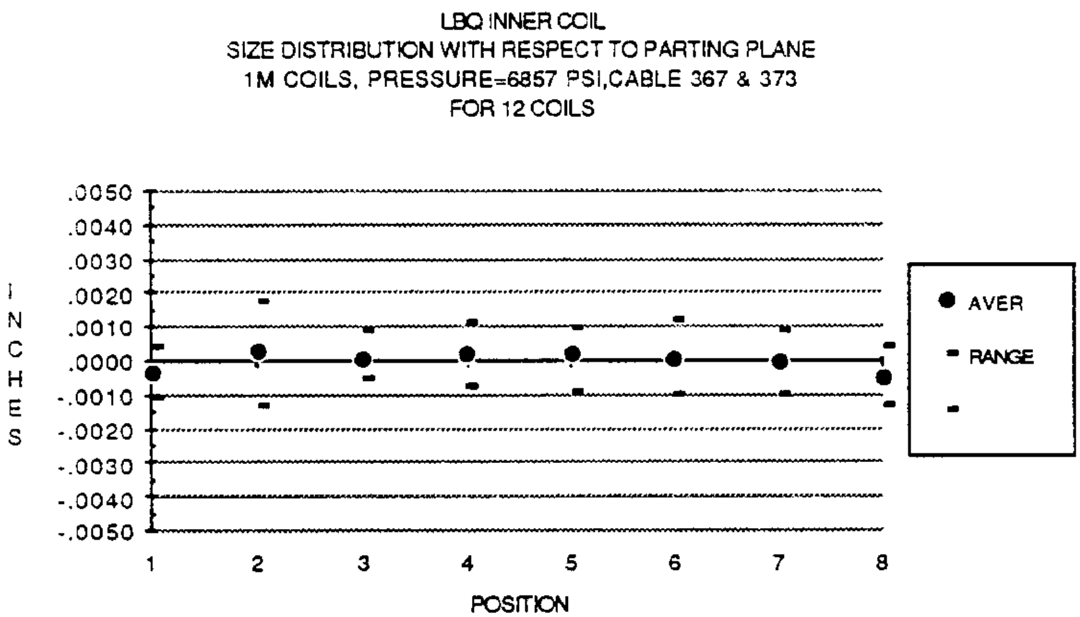


Figure 9. Coil Molding Press - Length of Press = 60' + 60' for Staging Table

PROGRESS TO DATE

The 1M tooling has been completed and is currently in use. The long 16.6M tooling is under construction with completion scheduled for March 1989. The 1M tooling utilizes existing Tevatron coil presses modified to provide the required two-stage loading. We have made four test coils of the SSC NC9 cross section. Coil measurements are being compiled. At Fermilab another magnet program is in progress to produce a series of low beta quadrupole magnets for a new detector installation. Tooling used in the quadrupole program is identical in design, function and materials as the SSC tooling, the only exception being coil cross section and cable and insulation type. Figure 10 plots the measurements of twelve (12) coils produced from this tooling.



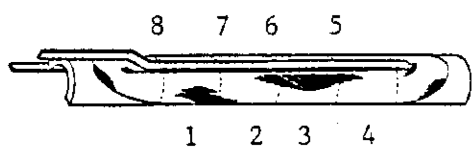


Figure 10. Size Distribution of 12 Coils at 6,857 PSI

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3. Tool and Manufacturing Engineer's Handbook, SME, 3rd edition, 15-17.
4. C. E. Dickey, "Coil Measurement Data Acquisition and Curing Press Control System for SSC Dipole Magnet Coils", these proceedings.